Mars Base Technology Program Overview

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Mars Technology Program has been developing advanced technologies needed for future Mars missions. Base Technology Program Element of Mars Technology Program addresses technologies that are applicable for multiple missions and can be characterized as longer term, higher risk, and high payoff technologies. These technologies are acquired primarily via competed NASA NRA process. This paper presents an overview of the current base technology portfolio. Criteria to assess the readiness level of these technology tasks will also be discussed.

I. Introduction

As integral part of NASA Mars Exploration Program (MEP), Mars Technology Program (MTP) managed by Jet Propulsion Laboratory has been developing advanced technologies needed for future Mars missions, including Mars Scouts. The two principle program elements of MTP are the Focused Technology and the Base Technology Programs. The Focused Technology Program addresses technologies that are specific and critical to near-term missions. One such example is Mars Science Laboratory (MSL) Focused Technology Program [ref 1]. The Base Technology Program, on the other hand, addresses enhancing technologies for near-term missions such as Phoenix and MSL, critical capabilities for competed missions such as Mars Scouts, and capabilities for Mars next decade missions which can be characterized as longer term, higher risk, and high payoff technologies.

The primary approach for MTP to acquire technologies in its Base Technology Program Element is to use the solicitation process of NASA Research Announcement (NRA). Over the past 3 years, NASA awarded 87 technology proposals with total funding of $75M approximately via NRA process. Among the awarded proposals, 60 proposals were selected in 2004 as part of MEP Advanced Technologies NRA which covers six high-priority technology areas: *Rover Technology, Subsurface Access, Planetary Protection, Advanced Entry, Descent and Landing (EDL), Telecommunication and Navigation, and* Technologies for Low Cost Missions (such as Mars Scout). The remaining 27 proposals were selected in 2002 and 2003 as part of *Mars Instrument Development Program (MIDP)* NRA. The period of performance for these tasks ranges from 18 months to 3 years.

In this paper, we will present an overview of the current technology portfolio for Mars Base Technology Program. The contents for each of six technology areas and MIDP will be introduced. Additionally, we will present an approach, which MTP plans to use to evaluate technology maturity for each of technology tasks. The approach is based on Technology Readiness Level (TRL) (see http://www.hq.nasa.gov/office/codeq/trl/trl.pdf for TRL definitions). However, additional efforts are made to define detailed but distinct criteria for hardware and software technology development. We will show examples to illustrate how we intend to use the proposed process.

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II. MTP Base Technology Program

As stated earlier, the current MTP Base Technology Portfolio consists of 87 tasks, which were selected by NASA via the competed NRA process. These tasks fall into the following 7 technology areas:

- Advanced Entry, Descent, and Landing (EDL)
- Rover Technology,
- Subsurface Access,
- Planetary Protection,
- Telecommunication and Navigation,
- Technologies for Low-Cost Missions, and
- Mars Instrument Development Program (MIDP).

We will introduce these technology areas and present a brief description for each task, which are under development.

(A) Advanced Entry, Descent, and Landing

Future Mars missions may need the capability to land much closer to a desired target and/or advanced methods of detecting, avoiding, or tolerating landing hazards. Therefore, "pinpoint landing" (within tens of meters to 1 km of a target site) and advanced hazard detection/avoidance capabilities will be crucial to meet future mission requirements. Relevant technologies include:

- ❖ Methodologies suitable for use in both advanced hypersonic entry guidance and aerocapture guidance;
- ❖ Methodologies for autonomously compensating for wind drift on a parachute or other drag device during low altitude, low speed flight;
- ❖ Methodologies (including sensors) suitable for autonomous onboard identification of a preselected landing site from a stored onboard terrain map, and guidance and navigation to the site; and
- ❖ Methodologies for navigation with radiometric data involving the use of orbiting "beacon" spacecraft, and for filtering of radiometric and/or sensor-based tracking data for autonomous navigation during entry, descent, and landing.
- ❖ Development of advanced active terrain mapping sensor providing increased range (>5 km), higher ranging accuracy (better than 5 m at 2 km and 0.04 meter at 80 m) higher field of regard (> 10x10 deg), high frame rate (>1 Hz), and
- ❖ Algorithms to interpret sensor data or fuse data from multiple sensors, to detect and/or avoid hazards, and/or to select sites that are safe and traversable by rovers.

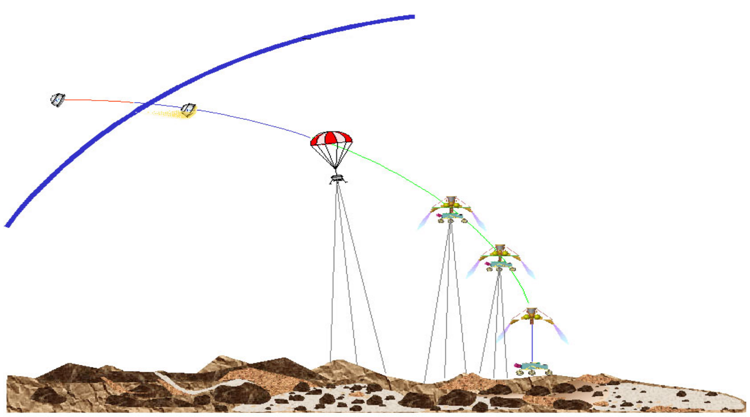

Figure 1. A Representative EDL Scenario

The current MTP Base Technology portfolio in advanced EDL consists of 11 tasks awarded under NASA MEP Advanced Technology NRA. A brief description of these tasks is summarized in Table 1.

Task Title/PI/Organization	Task Description
Multi-Sensor Hazard Assessment and Safe Site Selection *PI : Homayoun Seraji, Jet Propulsion Laboratory*	To develop and demonstrate the enabling technologies needed for autonomous safe landing of a spacecraft on a planetary surface using on-board terrain sensors (e.g. radar/camera/lidar). The landing site selection will be based on site safety, science return, and engineering constraints (e.g. fuel).
Passively Imaged, Multi-Cue HDA for Safe Landing *PI : Yang Cheng Jet Propulsion Laboratory*	To develop a passive-imaging-based Hazard Detection & Avoidance (HDA) system that can detect all relevant landing hazards (rocks, slopes, discontinuity and craters) in real time during EDL. The system will enable HDA for low cost, future Mars missions such as second-round Mars Scouts and enhance HDA for MSL and other large missions.
Rock Hazard Avoidance System (ROHAS) *PI: Karl Blasius, Raytheon Company, Santa Barbara Remote Sensing*	Raytheon and Arizona State University are developing a Rock Hazard Avoidance System (ROHAS) to recognize landing hazards during descent using real-time thermal IR imaging. The system hardware, a miniature camera, and real-time software/firmware components are being advanced from TRL2 (Technology Concept) to TRL4 (Breadboard Validation in a Laboratory Environment).
A Miniature Coherent Altimeter and Velocimeter (MCAV) for Terminal Descent Control *PI : Daniel Chang, Jet Propulsion Laboratory*	This task applies state-of-the-art integrated-optic components to develop a sensor that specifically addresses the shortcomings of RADARs for the terminal guidance of soft-landers. MCAV will provide cm/s-accuracy velocity and meter-accuracy altitude measurements at 10-100Hz update rates in a compact package. A prototype will be built and demonstrated.
Orbiting Beacon Navigation for Pinpoint Landing *PI: P. Daniel Burkhart, Jet Propulsion Laboratory*	The objective is to quantify position and velocity knowledge improvements using spacecraft to spacecraft UHF Doppler data by covariance analysis and simulated data processing. Algorithms needed for onboard processing of UHF Doppler data during EDL will be developed and prototype software will be demonstrated on a breadboard version of Electra.
Next Generation Radar for Improved Hazard Detection, Velocimetry, and Altimetry *PI: Gregory Sadowy, Jet Propulsion Laboratory*	A millimeter-wave landing radar provides high-precision altimetry, velocimetry and hazard detection in a small package and operates under all lighting and atmospheric conditions. We are developing state-of-the-art MMIC and antenna technologies and a system design that will enable development of a radar landing system operating at approximately 160 GHz.
Coupled Vision and Inertial Navigation for Pin-Point Landing *PI: Stergios Roumeliotis, University of Minnesota*	This work focuses on precise state estimation for pinpoint landing of spacecraft. Real-time estimation techniques are designed for aiding inertial navigation with image-based estimates for the motion and pose of the spacecraft. A Kalman filter will be designed and implemented that processes inertial measurements and images of visual surface features (craters/ridges/mountain peaks) acquired during the EDL.
Wind Drift Compensation using Parachute Control *PI: John McKinney, Boeing*	The objective is to demonstrate the feasibility of reducing Mars landing site errors during parachute descent by using Wind Drift Compensation Control. This is done by developing a simulation of a controlled gliding parachute, and validating the simulation by high altitude drop tests of controlled parachute systems.
Adaptive On-Board Navigation for Pinpoint Landing *PI: Robert Bishop, University of Texas at Austin*	The objective is to enable pinpoint landings utilizing a model-based navigation algorithm consisting of regulated banks of filters offering robustness to sensor failures and adaptability to atmospheric uncertainties. The guided entry will be navigated employing IMU and altimetry. The algorithm will be hosted on the MPO Electra for real-time verification.
Advanced Entry Guidance *PI: Kenneth Mease, University of California at Irvine*	Mars landers for future missions will require greater landing accuracy and in some cases higher lift-to-drag configurations. Entry guidance algorithms, that accurately steer a range of vehicle configuration types to a specified parachute deployment condition, are being developed. The performance of the algorithms will be verified by extensive testing.
Spacecraft-to-spacecraft EDL Navigation *PI: Pieter Kallemeyn, Lockheed Martin Space Systems*	The objective of this study is to simulate and analyze improved delivery accuracy using radiometric tracking data between the lander and an orbiting asset. Studies would be performed using Doppler and range tracking to determine a telecommunication and navigation system design that provides the best results.

Table 1: Base Technology Portfolio for Advanced Entry, Descent, and Landing

(B) Rover Technology

Rover Technology research in MTP is developing new capabilities for autonomous planetary surface exploration, including long-range traverse, science target approach and instrument placement, and onboard science data processing. Core technical capabilities that are being expanded under current funding include: proximal, regional, and global navigation; terrain classification; position estimation using visual and inertial methods; manipulation planning and control; and onboard contingent planning and execution. In addition, novel mechanical systems for mobility and sampling are being developed to aid these objectives, and field tests are being performed to exercise technology and expand the envelope of mission concepts.

Software products from all research are required to be delivered into the MTP software infrastructure named "CLARAty"[1]. Complementary integration and validation efforts are conducted under the MTP Focused Technology Program to infuse these technologies into future missions. Target missions are MSL where technology components are most mature, or Scout missions, Mars Sample Return (MSR), and Astrobiology Field Laboratory (AFL), otherwise. The current MTP Base Technology portfolio in Rover Technologies consists of 11 tasks awarded under NASA MEP Advanced Technology NRA. A brief description of these tasks is summarized in Table 2.

Task Title/PI/Organization	Task Description
Autonomous Long Range Localization *PI: Ronxing Li, Ohio State University*	The goal of this project is to develop an Incremental Bundle Adjustment (IBA) Technology for long-range autonomous rover localization at an accuracy of 0.2% (10m over 5km) in a rough terrain environment. Autonomous on-board rover localization will be supported by remote landmarks and a 3D ground image network.
Reliable & Efficient Long Range Autonomous Rover Navigation *PI: Tony Stentz, Carnegie Mellon University*	This task is developing perception, path planning, and orbiter map interpretation software to improve the reliability and efficiency of autonomous rover traverses. The task will enable planetary rovers to exceed one kilometer in a single-command autonomous traverse, while minimizing resources expended and the risk of rover loss.
Rover Navigation for Very Rough Terrain *PI: Reid Simmons, Carnegie Mellon University*	This task is to develop algorithms to autonomously drive rovers in areas that are currently beyond the capacity of existing approaches. The approach is to explicitly model vehicle dynamics and rover-terrain interaction and to search this high-dimensional space using efficient stochastic planning methods.
Very Rough Terrain Motion Planning for Rovers *PI: Alonzo Kelly, Carnegie Mellon University*	This task is developing new algorithms to address the particular challenges of rover motion planning. High fidelity mobility models are used to implement continuous motion primitives which adapt to 3D terrain shape, differential constraints, wheel slip, and controller transfer functions for any rover model. A higher level motion planner is constructed using these motion primitives
Multi-Sensor Terrain Classification and Terrain-Adaptive Navigation in Very Rough Terrain *PI: Steven Dubowsky, MIT*	This task aims to develop sensing and navigation methods to allow future rover systems to safely access very rough terrain. Improved stereo-vision based range imaging, hazard detection, and robust multi-sensor terrain classification algorithms will be developed. Improved algorithms will also be developed for navigation planning, trajectory generation, and trajectory following in challenging terrain.
Semi-Autonomous Rover Operations (SRO) *PI: Michael Ravine, Malin Space Science Systems*	To demonstrate a solar powered, 25 kg rover capable of traversing more than 10 km across Mars-like terrains in a "semi-autonomous" fashion based on meter-scale resolution overhead imagery and with contact with the operators for short windows once per day. Such a rover could investigate localized targets of high science value without the mission having a precision landing capability.
SCAIP: Integrated System for Single Command Approach and Instrument Placement *PI: Paul Backes,*	SCAIP will enable a rover to autonomously travel to a designated science target from 10 meters away, and precisely place an instrument on that target with a single command without additional human interaction. Auto-Placement, predictive target tracking, vision-guided manipulation, automated target selection, and target hand-off between rover cameras will

Jet Propulsion Laboratory	be developed and integrated into the SCAIP system.
Whole Rover-Arm Coordination *PI: Oussama Khatib, Stanford University*	This task will develop technology to enable the three degrees-of-freedom of rover mobility to be utilized in rover-based manipulator activities. The technology will be used to enable core sample acquisition from a low-mass rover and is valuable to a sample return mission which utilizes a small "fetch" rover to acquire rock core and regolith samples and return them to a lander-based ascent vehicle.
Universal Decision-Layer Executive *PI: Ari Johnson, USRA-RIACS*	The objective of this project is to develop a general, robust and verifiable plan execution capability for spacecraft and rovers. The executive will be able to handle plans ranging from simple commanding sequences to complex concurrent plans for maximizing utility in uncertain environments, while handling failures, and responding to opportunities.
Mechanized Sample Handler (MESH) for Mars *PI: Kiel Davis, Honeybee Robotics, Ltd.*	The Mechanized Sample Handler (MeSH) effort is developing a miniature end-to-end sample processing and distribution system that enables in-situ analysis of various sample types by analytical instruments on Mars. MeSH employs a low power attrition mill capable of reducing 5-cc basalt core samples to <150-micron particle sizes in <30 minutes.
SILVRCLAW - Inflatable, Rigidizable Rover Wheel *PI: Greg Mungas, Firestar Engineering*	Enhanced robotic surface exploration requires the capability to traverse significant distances in widely varying terrain conditions. This task is developing a long-range roving architecture based on enhanced mobility with Stowable, Inflatable, Large, Vectran, Rigidizable, Cold-resistant, Lightweight, All-terrain, Wheels (SILVRCLAW). This technology development leverages detailed FEM (Finite Element Modeling) analysis and testbed facilities developed for prior inflatables work.

Table 2: Base Technology Portfolio for Rover Technologies

(C) *Subsurface Access*

The main goal of MTP Subsurface Access research is to develop enabling technologies to explore the Martian subsurface. This includes ground-based subsurface mapping techniques such as ground penetrating radar devices; methods of physical access to subsurface samples such as coring and sampling drills; and subsurface instrumentation such as borehole spectrometers. General instrument development is included in the Mars Instrument Development Project (MIDP). Some of these systems involve the development of science instruments that can be brought to a subsurface sample. Others bring samples from the subsurface to elements on the surface. Drilling depths of interest may be roughly classified as shallow (less than one meter), moderate (greater than one meter and less than 50 meters) and deep (greater than 50 meters). All of these technologies must function in the unique environment of the Martian subsurface. This drives the development of rugged, low-mass, low-power designs that must be highly autonomous.

Given the increased uncertainties associated with operating such systems, these tasks aim to bring enabling technologies to high Technology Readiness Levels (TRLs) so that they may be readily utilized by future missions. In most cases, achieving this high level of maturity will necessitate field testing as well as other relevant environmental tests. The current MTP Base Technology portfolio in Subsurface Access consists of 4 tasks awarded under NASA MEP Advanced Technology NRA. A brief description of these tasks is summarized in Table 3.

Task Title/PI/Organization	Task Description
Mars Integrated Drilling And Sampling System (MIDAS) *PI: Scott Stanley, Alliance Spacesystems Inc.*	The MIDAS system will retrieve samples from rocks, soil, and up to 0.5m deep regolith for deposition into instruments or storage containers. MIDAS combines mature 5 degree-of-freedom robotic arm and Ultrasonic/Sonic Driller/Corer technologies with a new interchangeable bit mechanism and a variety of specialized bits.
Modular Planetary Drill System *PI: Paul Bartlett,*	Honeybee Robotics is collaborating with the Jet Propulsion Laboratory to develop an ultrasonic sampler capable of penetrating one half-meter into Mars regolith, requiring very low forces. The TRL of the ultrasonic penetrator, currently at 4, is being advanced to TRL 6 with the added

Honeybee Robotics, Ltd.	capability of robotically acquiring and delivering samples.
Mars Integrated Drilling And Sampling System *PI: Jose Guerrero, Swales Aerospace*	The Modular Planetary Drill System (MPDS) is a three-year technology development program to advance a 10-meter field-proven TRL-4 deep drilling system to satisfy NASA's 0.5-20m subsurface access needs and possibly beyond. The resulting TRL-6 technologies will provide advanced capabilities for subsurface access on future planetary and lunar exploration missions.
X-Ray Fluorescence for Mars Subsurface Access *PI: Warren Kelliher, NASA Langley Research Center*	LaRC, in conjunction with Applied Physics Laboratory (University of Washington), is producing a prototype X-ray Fluorescence Spectrometer to provide elemental analysis of Martian strata deployed down a borehole. The instrument diameter is 30 mm. and a study is being conducted to determine the feasibility of a diameter reduction to 10mm

Table 3: Base Technology Portfolio for Subsurface Access

(D) Planetary Protection

Planetary protection aims to preserve the biological and organic conditions of the solar system bodies for future exploration and at the same time protect the Earth from potential extraterrestrial contamination. Planetary protection requirements for each mission are based on the types of encounter it will have (flyby, orbiter, or lander) and the potential of the mission's destination to provide insight into the origin of life. To implement planetary protection requirements, current technologies need to be advanced to satisfy planetary protection requirements for surface, subsurface and atmospheric missions as well as those technologies that allow sample acquisition for in situ life detection or sample return. These technologies include cross-contamination risk assessment and prevention; pre-launch bioburden reduction and validation; heating of orbital debris during atmospheric entry at Mars; and sample return issues including containment, handling and sample analysis.

The current MTP Base Technology portfolio in Planetary Protection consists of 7 tasks awarded under NASA MEP Advanced Technology NRA. A brief description of these tasks is summarized in Table 4.

Task Title/PI/Organization	Task Description
The Rapid Single Spore Enumeration Assay (RapidSSEA) *PI: Adrian Ponce, Jet Propulsion Laboratory*	RapidSSEA is being developed to validate bioburden reduction on spacecraft surfaces. RapidSSEA is based on imaging and counting individual bacterial spores in a microscope field-of-view. The contrast is generated by a highly luminescent complex that forms when dipicolinic acid is released from spores during germination and binds to terbium ions in the surrounding medium. From sampling to result, RapidSSEA can be performed within an hour.
Contamination Transport for Planetary Protection *PI: Partha Shakkottai, Jet Propulsion Laboratory*	A near field particle transport model is being developed to describe how particles from spacecraft surfaces are transported to the ground and to other surfaces due to the influence of Martian winds. Empirical particle adhesion data and theoretical estimates form the input data. Wind tunnel tests at atmospheric conditions and in simulated Martian conditions will provide validation data.
Spore Adhesion for Contamination Transport Models *PI: Ying Lin, Jet Propulsion Laboratory*	The objective of this task is to obtain knowledge and data sets of spore association and adhesion to dust particles and spacecraft materials. These information are necessary for developing high fidelity contamination transport models in support of Mars landing and sample return mission PP requirements
Development of Biobarrier Technology *PI: Yuki Salina, Jet Propulsion Laboratory*	The objective of this task is to provide fundamental biobarrier technology (microbial reduction method, materials, structural designs, deployment designs, sealing designs, reliability test results) to meet the planetary protection bioburden requirements of Category IV-C. Biobarrier technology compatible with dry heat microbial reduction as well as hydrogen peroxide microbial reduction will be developed.
Cleaning To Achieve Sterility *PI: Roger Kern,*	The cleaning to achieve sterility task is to evaluate cleaning effectiveness of spacecraft materials, component/piece parts, and subsystems using three state-of-art cleaning systems. The goal of this research is to develop an alternate method to create "effectively sterile" surfaces to reduce costs, risk, and materials constraints of dry heat sterilization and common cleaning

Jet Propulsion Laboratory	practices.
Contained Sample Handling & Analysis System (CSHAS) *PI: Joe Parrish,* *Payload Systems, Inc.*	The Contained Sample Handling and Analysis System (CSHAS) will adapt the International Space Station Cell Culture Unit (CCU) flight system for use on Earth to perform analysis, testing, preparation and other functions in support of defined Mars returned sample handling and analysis protocols.
Development of Mars Orbital Debris Analysis Code *PI: Walter Bruce, NASA* *Langley Research Center*	The Development of Mars Orbital Debris Analysis Code task is to develop a thermal analysis tool that can be used to quickly determine if small debris will meet the planetary protection sterilization requirements at any point along a breakup trajectory during Martian entry.

Table 4: Base Technology Portfolio for Planetary Protection

(E) Telecommunication and Navigation

Telecom and Navigation technology investments, specifically relate to proximity-link-relay communications and in situ radio-based navigation scenarios. Relay communications technologies are aimed at significantly increasing science data return from a wide range of future exploration assets (e.g., landers, rovers, aerobots, microprobes) while minimizing mass, volume, and energy needs. Next-generation network protocols will ensure interoperability while enabling efficient operations. Additionally, extraction of radiometric information from these proximity links can support precision in situ navigation for scenarios such as approach, surface mobility, and on-orbit rendezvous.

The current MTP technology portfolio in Telecommunication and Navigation consists of 12 tasks awarded under NASA MEP Advanced Technology NRA. A brief description of these tasks is summarized in Table 5.

Task Title/PI/Organization	Task Description
X-Band Agile Beam Transmitter *PI: Ronald Pogorzelski ,* *Jet Propulsion Laboratory*	This task is directed at decreasing the cost of electronically steerable antennas through the reduced complexity achievable via a revolutionary concept in beam agility based on coupled electronic oscillators. An X-band transmitter based on this concept and compatible with the X-band receive option of the Electra payload is being developed.
Reprogrammable Transceiver Modem *PI: Doulgas Merz,* *CMC Electronics Cincinnati*	The reprogrammable transceiver modem ASIC enables the future development of compact, low power, multi-mission capable radios. Most of the modem's components are incorporated into a single ASIC including microprocessor, memory, C&DH interface, discrete I/O, SSR interface, demodulation, and baseband processing. The modem's functionality is based upon the Electra/Electra-Lite transceivers.
X Band Appliqué for ELECTRA *PI: Richard Hunter,* *CMC Electronics Cincinnati*	The X-band appliqué interfaces directly to an ELECTRA transceiver to provide a UHF high-data-rate proximity link and an X-band direct-to-Earth link. The "receive" section of the appliqué consists of an X-band low-noise amplifier and mixer with an output frequency covering a range of 390 MHz to 450 MHz. The "transmit" section of the appliqué consists of a mixer and an X-band amplifier cascade with an output stage of the cascade consisting of an X-band power amplifier.
A Proximity Microtransceiver for Interoperable Mars Communications *PI: William Kuhn,* *Kansas State University*	This task will develop a UHF half-duplex micro-transceiver measuring in the 1cm3 range, weighing less than 10 grams, and operating at fractions of a Watt. The micro-transceiver will support a subset of Prox-1 capability and communicate collected scientific results to earth by relaying data through Mars orbiters, as well as support surface-to-surface links for geographically extended local exploration.
Coding System for High Data Rate Mars Links *PI: Christopher R. Jones,* *Jet Propulsion Laboratory*	This task is developing a capacity-approaching coding system for Mars proximity communications requiring data rates in excess of 5 Mbps. Infuse code-programmable encoding and decoding modules with the Electra radio set. These modules should be amenable to space qualification for operation in orbiter relays.
Autonomous Radio for Proximity Links *PI: Jon Hamkins*	The goal of this task is to develop autonomous radio receiver technologies, and demonstrate them on Electra. The carrier frequency, data rate, modulation type, modulation index, pulse shape, etc. are automatically determined from the incoming signal, avoiding the need for complicated

Jet Propulsion Laboratory	reconfiguration commands sent from Earth.
Fast and Accurate EM Modeling *PI: Oscar Bruno, California Institute of Technology*	Our task seeks to produce a fully-validated simulation infrastructure, with superior capabilities in terms of modeling generality, accuracy and speed, for the prediction of full fidelity near-fields and far-fields (including multi-path and impedance behavior) in complete multi-material, antenna-spacecraft structures.
Large Diameter Fresnel Lenses as Optical Communication Optical Receivers *PI: Hamid Hemmati, Jet Propulsion Laboratory*	For free-space Laser Telecommunications, NASA requires large diameter, low-cost, and rapidly manufacturable Earth-based optical receivers to facilitate higher data-rate downlink from remote spacecrafts. Under MTP funding, JPL is custom developing and evaluating large (2 to 5-meter) diameter Fresnel lenses, an array of which will yield a very large effective aperture.
Vitreous UHF Proximity Link Antennas for Future Mars Telecommunications Orbiters and Landers *PI: Ray Lovestead, Ball Aerospace*	The purpose of this study is to develop Vitreous® antenna elements and arrays to provide space savings on both Mars orbiters and landers. A relatively low frequency antenna, designed as a wire mesh, will function at its intended frequency yet appear transparent at higher frequencies. Therefore a low frequency antenna can be mounted directly in front of a higher frequency antenna. Ball Aerospace will design both Orbiter and Lander Vitreous® UHF/X-band antennas for use on future Mars missions.
Mars Approach Navigation using In-Situ Orbiters *PI: Todd Ely, Jet Propulsion Laboratory*	This task is developing navigation algorithms and prototype software to be hosted on Electra to process Electra-based radiometric data and determine trajectories during final approach in real-time. Target demo on the Mars Science Laboratory (MSL), which will have a version of Electra on-board.
Data Compression for Stereo Image Pairs *PI: Matthew Klimesh, Jet Propulsion Laboratory*	To develop techniques that achieve improved stereo image pair compression by exploiting the correlation between the left and right images, and that are practical to use on a Mars rover. We are also quantifying the effects of lossy image compression on stereo ranging accuracy.
Next Generation Mars Relay Protocol Suite *PI: Christopher.Krupiarz, Applied Physics Laboratory, Johns Hopkins University*	The Next Generation Mars Protocol Suite project is studying the integration of current international network standards along with cutting edge protocols such as Delay Tolerant Networking to address the need to reliably deliver science data from a future Mars network.

Table 5: Base Technology Portfolio for Telecommunication and Navigation

(F) *Technologies for Low-Cost Missions*

This technology area supports all future Mars missions, and specifically focuses on Scout missions which are competed by NASA. Several different technologies are needed to enable various types of low cost missions to be developed and flown. While not all potentially beneficial technologies have been solicited or funded, the following classes of technologies were considered for funding, and several promising candidates selected.

(a) Entry, Descent, and Landing (EDL) for small entry probes (1 task)

Small entry probes present unique challenges since their severe mass, power, and volume constraints generally mean less accurate EDL capabilities than larger systems currently envisioned in the future Mars Exploration Program (MEP). Therefore, increasing the EDL capabilities of small probes could lead to future breakthroughs in low cost missions.

(b) Lightweight propulsion components (7 tasks)

The propulsion system constitutes a large fraction of any low cost mission mass. Reducing the mass and power of the propulsion system allows more payload and more science to be accomplished. Examples of important propulsion system technologies are low mass tanks, filters, regulators, and valves. Optimized thrusters for lower mass systems require lower minimum impulse bit control. Finally, increases in propellant performance (Isp) would reduce the required propellant mass.

(c) Aerial vehicle technology (4 tasks)

Aerial vehicles (defined here as airplanes and balloons) require robust, lightweight deployment technologies. For this class of low cost missions, deployment most likely occurs during the descent phase. Also critical to this type of low cost mission is guidance and navigation during the atmospheric flight.

(d) Mars Surface Solar Power Technologies (3 tasks)

Landers, rovers, and aerial vehicles will benefit from technologies that will increase power levels and prolong the useful life of space solar power systems. Technologies to provide high efficiency solar cell system, as well as practical (low power, low mass) dust mitigation techniques, are included.

The current MTP technology portfolio in Telecommunication and Navigation consists of 12 tasks awarded under NASA MEP Advanced Technology NRA. The fifteen tasks funded under MTP Technologies for Low Cost Missions are summarized in Table 6.

Task Title/PI/Organization	Task Description
Strapon High-altitude Entry Reconnaissance and Precision Aeromaneuver System *PI: J. Balaram, Jet Propulsion Laboratory*	To develop control and electro-mechanical system design for a new precision landing capability for Mars Scout-class vehicles. Unlike approaches using thrusters for bank angle control of lift, a low-cost, compact, fully internal moving-mass system is investigated. This enables science target access hitherto possible only on expensive missions.
Low Cost Controllable Solid Martian Descent Stage *PI: David McGrath, ATK Inc.*	The objective of this project is to design a low-cost, controllable solid, soft landing system (SOFTLAND™) for Scout-class missions with 40% lower weight, 60% lower volume and 50% lower cost than comparable liquid systems. The effort includes development of a vacuum and space compatible propellant optimized for cold temperature operation.
Quad Piston Propellant Pump, Scaled for Low Cost Missions *PI: John Whitehead, Lawrence Livermore National Laboratory*	This task is a step toward implementing launch vehicle principles on a scale small enough for Mars science. Propellant fractions near 90% on a 100-kg scale would apply to Mars ascent, e.g., to reduce sample return mission cost. Encouraging 2005 test results include high liquid throughput and low gas consumption.
Hydrazine MilliNewton Thruster (HmNT) *PI: J. Morgan Parker, Jet Propulsion Laboratory*	This development will dramatically improve the minimum impulse bit capability (100 X) compared to the current state-of-the-art (SOA) hydrazine thruster. The goals of the HmNT are to demonstrate steady state thrust of 20–50 milliNewtons (mN), and minimum impulse bit of <50 microNewton-sec (µN-s). The HmNT technology can replace reaction wheels, saving mass, power, volume, and cost.
Ultralight Diaphragm Propellant Tank *PI: Paul Woodmansee, Jet Propulsion Laboratory*	The objective of this task is to develop and test an ultra-light diaphragm propellant tank in a simulated flight environment to reach TRL 6. This tank will have half the mass of a current state of the art diaphragm propellant tank. The expected mass savings per mission will range from 10 to 20 kg (depending on the mission), which can be applied directly to the payload.
Lightweight, High Efficiency, Smart, Radial Arm Filter Assembly *PI: John Barnett, VACCO Industries, Inc.*	The filter design objective is to develop a TRL 6 component with reliable, self monitoring, high efficiency and especially low mass filtration technologies. VACCO's patented design for multiple radial arm etched discs will be incorporated allowing the filtration and flow areas to be increased, thus decreasing the overall size and mass of the filter assembly.
Low Mass Integrated Pressure Regulator/System Filter Module *PI: Jasen Cheung, VACCO Industries, Inc.*	The objective is to develop a TRL 6 component that integrates an advanced precision high pressure regulator and high pressure system state-of-the-art Etched Disc Filter into a single compact low mass "pressure regulator/system filter" assembly. This provides a lighter weight propulsion system with reduced system complexity, lower cost, and improved reliability for helium fed propulsion systems.
Nitrous oxide Oxidizer/Fuel Blend Optimized Breakdown System (NOFBOBS) *PI: Greg Mungas, Firestar Engineering*	An optimized liquid Monopropellant blend with the following characteristics: 1) ~300s vacuum equivalent Isp (demonstrated); 2) Propellant density 1-2 times that of tanked monopropellant hydrazine; 3) < -80 deg C freezing point; 4) 10fold improvement in impulse bit 5) Non-toxic, 6) Self-pressurizing, 7) Low cost manufacturing.
Helium Superpressure Balloons for Mars Exploration	This task consists of a set of six Earth atmosphere flight tests of prototype superpressure balloons suitable for use at Mars. Each flight is preceded by a

PI: Jeffery L. Hall, Jet Propulsion Laboratory	sequence of design, fabrication, assembly and ground test activities. We are focused on the challenging problem of safe aerial deployment and inflation of the prototype balloons. The test flights take place in the Earth's stratosphere (31 km altitude).
Mars Montgolfiere Balloons *PI: Jack Jones, Jet Propulsion Laboratory*	Ground-deployed, solar-heated hot air balloons, or Montgolfieres, have long been flown in Earth's upper stratosphere. Similar sized balloons at Mars have been shown to be capable of flying long duration summer, polar missions, while sampling polar ice for evidence of life. The objective is to demonstrate the high altitude deployment of Montgolfieres (20-30-m) required for this type of missions.
Mars Advanced Technology Airplane for Deployment, Operations, and Recovery *PI: Lawrence Lemke, NASA Ames Research Center*	MATADOR is a project to develop the next generation of Heavier-Than-Air craft for flight in the Mars atmosphere. It employs small thrusters to maintain attitude control during deployment and approach to landing, and a large thruster to permit a soft landing. This allows a safer deployment with minimum loss of altitude and the possibility of an extended mission on the surface.
Mars Celestial Navigator *PI: James Alexander, Jet Propulsion Laboratory*	The objective is to develop a low power (goal < 8 watts), low mass (goal ~600 grams) smart instrument capable of determining latitude and longitude from a balloon or airplane on Mars. The hardware includes a star camera, sun camera, IMU, CPU, and the software for the position determination. Additionally, a three-axes attitude determination system is developed during the course of this task.
Solar Array Dust Removal System (SADRS) for Mars *PI: Steve White, Able Engineering*	The effort demonstrates the vibratory Solar Array Dust Removal System (SADRS), a low-cost method for increasing Mars-based solar array life utilizing piezoelectric vibrators) by design, analysis, fabrication and test in simulated Mars surface dust conditions of a SADRS breadboard panel and a high-fidelity Engineering Model in preparation for space environmental qualification.
Electrodynamic Screen for Dust Particle Removal from Solar Panels *PI: M.K. Mazumder, University of Arkansas at Little Rock*	A self-cleaning transparent electrodynamic screen (EDS) to protect Mars solar panels from dust accumulation has been developed and tested using JSC Mars-1 dust simulant. When energized at $2W/m^2$, the EDS removed dust particles, restored optical transmission and regained the voltage output. Screen geometry is being optimized for maximum dust removal efficiency at minimal power consumption.
Mars Optimized Solar Cell Technology (MOST) *PI: Paul Stella, Jet Propulsion Laboratory*	This task is developing solar cells that will function at maximum efficiency on the surface of Mars. First-generation versions of the Mars-optimized three-junction cells are projected to have up to 10-15% higher efficiency compared to state-of-the-art triple-junction solar cells. Second-generation Mars-optimized cells (advanced three- and possibly four-junction solar cells) are projected to have 30-40% higher efficiency compared to present state-of-the-art triple-junction solar cells at Mars equatorial latitudes.

Table 6: Base Technology Portfolio for Low Cost Mission Technologies

(G) Mars Instrument Development Project (MIDP)

The main objective of MIDP (Mars Instrument Development Program) is to develop ground demonstrated miniature instruments that are at TRL 3 into space qualifiable hardware (TRL 6); ready for response to Mars missions Announcement of Opportunity (AO).

Most of the existing instrument R&D programs (e.g., PIDDP) only support up to breadboard level (TRL 3, 4) and there is a need to carry such instruments to flight qualifiable status to respond to flight AO. Often the flight AO has only limited time and financial resources, and can not afford such hardware development processes. Thus the aim of the MIDP task is to bridge the existing gap between instrument R&D programs and hardware requirements for flight programs.

All the instruments being developed under MIDP have been selected through a highly competitive NRA process, and employ state-of-the-art technology. For example, MIDP I (1998-2000), MIDP II (2003-2005), and MIDP III (2004-2006) has selected 10, 16, and 11 instruments respectively. Working with PIs, JPL has been managing the MIDP Tasks since September 1998. Depending on instrument maturity, Mars Technology Program will arrange integration of instruments with an available rover (K9 Rover, FIDO, Rocky 7 or Rocky 8) and test in a Simulated Environment.

Tasks funded under MIDP II and III are listed in Table 7 and 8. As a successful story, 3 out 8 instruments selected by Mars Science Laboratory (MSL) AO are being developed under MIDP.

Task Title	PIs
Characterization of Mars Atmospheric Dust (CMAD)	Phillip Jenkins (OAI)
Argon Geochronology Experiment	Timothy D. Swindle (U of Arizona)
MAHI	Paul Lucey (U of Hawaii) Jeffrey Gillis-Davis (U of Hawaii)
Deployable Instruments	Gregory Delory (U of California)
Miniature Hydrate Sensor	Richard Elphic (LANL)
Raman Spectroscopy System	Bruce McIntosh (Hamilton Sundstrand)
Mars Underground Mole	Carol Stoker (ARC)
Mineral Identification & Composition Analyzer (MICA)	John Marshall (SETI) Joe Martin (Equinox) Dan Scheld (Equinox)
CHEMIN	David Blake (ARC)
Tunable Laser Spectroscopy	Chris Webster (JPL)
Electrospray Ionization/Ion Mobility Spectrometer	Isik Kanik (JPL) Luther Beegle (JPL)
Mars Oxidant & Radical Detector (MORD)	Albert Yen (JPL)
Mars Ground Penetrating Radar	Sam Kim (JPL) Neil Chamberlain (JPL)

Table 7: Technology Portfolio for MIDP II

Task Title	PIs
Drill Integrated Neutron Spectrometer	Steven Gorevan (Honeybee) Philip Chu (Honeybee) Richard Elphic (LANL)
Automated Drilling	Brian Glass (ARC)
Optical System for LIBS	Roger Wiens (LANL) Sam Clegg (LANL)
Rover GPR	John Grant (Smithsonian) Kevin Williams (Smithsonian)
Autonomous Meteorology Station	Mark Richardson (CIT)
Low Force Sample Acquisition System	Scott Stanley (Alliance)
HYDRA	Lonne Lane (JPL)
Mars Borehole Spectrometer	William Smythe (JPL)
Mars Atmosphere Temperature and Humidity Sounder (MATHS)	Michael Janssen (JPL)
Atmospheric Electron X-ray Spectrometer	Jaroslava Wilcox (JPL)

Table 7: Technology Portfolio for MIDP II

III. Technology Readiness Level Evaluation

The Technology Readiness Level (TRL) scale is from 1 to 9, where 1 represents a technology principle and 9 represents a technology flown successfully in space. Flight projects that are not technology demonstration missions typically don't like to accept the risk of including a technology with a TRL of less than 6 in their design concept. TRL 6 corresponds to a technology maturity level with a system/subsystem model or prototype demonstrated in a relevant environment (ground or space).

Using the NASA definitions for Technology Readiness Levels (TRL), we have established a more in-depth set of TRL 4-6 requirements for hardware and software developers. Note that TRL 4-6 are to technology maturity levels of interest for technology funded by MTP. By establishing requirements for the technologists and regularly assessing the progress against those requirements, the flight project is able to assess the maturity, the developmental risk, and any system implications that this new technology poses to the mission and respond accordingly. The technologist also benefits, by having clear knowledge of expectations.

To ensure the objective of achieving TRL 6 – subsystem/ system model or prototype demonstrated in a relevant environment (ground or space) – for MTP technology deliverables, major technology products delivered to MTP must go through a formal review, where states of technology maturity are ironed out and assessed via information provided in an TRL evaluation form. The TRL evaluation review is convened by and chaired by MTP Element Managers.

The purpose of the TRL evaluation form is to assess the readiness of a technology deliverable and provide crucial information needed for infusion into future missions. In preparation for the anticipated technology infusion, during the technology development stage the Task Manager responsible for a particular hardware/software deliverable provides an assessment of TRL evaluation criteria for the anticipated states of the technology product at delivery. This early assessment of technology maturity criteria must be established and concurred by the Element Manager. During the TRL evaluation review, the final states of technology maturity with respect to the pre-established criteria are then evaluated for acceptance of the technology product by MTP.

An example of technology maturity criteria for hardware deliverables is shown in Figure 2. The top portion of the above form for hardware deliverables provide definitions of TRL 4-6 as well as technology product description and responsible individuals/organization. Results of the TRL assessment and approval/concurrence signatures are at the bottom portion of the form. The example shown here describes Long-Life, Extreme Cold Environment Actuator (Motor, Gearbox, and Drive Electronics) technology developed under the MTP's MSL Focused Technology program.

Evaluation criteria required for TRL 4 assessment involve information pertaining to system requirements, description of "relevant environment," state of drawings, power analysis, mass analysis, functional test, compliance of test hardware to requirements, and delivery of end-item data package.

In order to permit TRL 5-6 assessment, we request additional information regarding interface control document, mechanical analysis, electrical analysis, thermal/packaging analysis, environmental test, failure history/trend, and extent of change required for project use. When flight projects infuse a TRL 5-6 technology, this added information is essential to permitting an accurate assessment of work completed, work to-go, and the risk associated with accepting the technology.

Since TRL 6 involves development beyond component/breadboard-level development and testing, results typical of matured technology products like non-flight like parts/materials used, availability of flight-quality equivalents for electronic parts, and reliability analysis are also requested. Finally, for MTP tasks with significant funding investments, Quality Assurance (QA) work on the delivered hardware may have been done, and such information would help mitigating the risk of infusing technology that has not been flown.

With the information provided by the Long-Life, Extreme Cold Environment Actuator, we assessed that if the technology development effort achieves the results as described at the time of delivery (well-defined requirements and matured design/interface/test states of the Engineering Development Unit), the technology is consistent with being at TRL 6, i.e., system/subsystem model or prototype demonstrated in a relevant environment (ground or space).

TRL 4: *Component/breadboard validation in laboratory environment*	**MTP Technology Readiness Level Evaluation for Hardware** **TRL 6:** *System/subsystem model or prototype demonstration in relevant environment*	**TRL 5:** *Component/breadboard validation in relevant environment*

Technology Product Description	Cognizant Engineer/Task Mgr	Organization	MTP Element	Element Manager	Date
Long-Life, Extreme Cold Environment Actuator (Motor, Gearbox, and Drive Electronics)	*Michael R Johnson*	*352*	*MSLFT Flight System HW*	*Michael J Mangano*	*7/28/05*

EVALUATION CRITERIA	**Rq'd**	**Anticipated Status/Results at Delivery**	**Final Status/Results**	**Comments**
1. Functional and environmental requirements of the flight system.	4/5/6	*50M revs, 1500 thermal cycles (-120°C to +85°C), operate in vacuum and Mars atmosphere, brushless DC actuator, UART interface.*		
2. Description of "relevant environment."	4/5/6	*Thermal cycling the Engineering Development Unit (EDU) for 1500+ cycles in 1atm N2.*		
3. Design drawings.	4/5/6	*Schematics and Electronics Fabrication drawings, Electronic Parts List, Verilog code for Controller ASIC, Op-Amp detailed designs, Electronic housing drawings, and Actuator detailed drawings at Aeroflex.*		
4. Interface control documents.	5/6	*Actuator Mechanical ICD, Electronics Assembly MICD, and Controller ICD.*		
5. Mechanical analysis (including analytical models).	5/6	*Stress and fatigue (vibration/shock included), and motor magnetic torque.*		
6. Electrical analysis (including analytical models).	5/6	*Parts stress, worst case, single event effects, and control loop for throttle valve.*		
7. Thermal and packaging analysis (including analytical models).	5/6	*Temperature rise and thermal cycle (physics of failure)*		
8. Power analysis (including analytical models).	4/5/6	*Mechanical performance based on 15amps at 30V.*		
9. Mass (and CG) analysis.	4/5/6	*Mass for actuator (mechanical portion) and controller (drive electronics portion).*		
10. Non-flight like parts/materials used.	6	*Some passive components for the controller are commercial-grade.*		
11. Availability of flight-quality equivalents for electronic parts.	6	*None, but commercial parts upgrade plan identified.*		
12. Reliability analysis.	6	*Thermal cycling analysis (physics of failure included), radiation analysis and tests, electronics assembly manufacturing processes, ball-bearing life, and gear/lubricant life.*		
13. Functional test (analytical models and idiosyncrasies included).	4/5/6	*Breadboard#3 tests all controller functions using flight components over full temperature range.*		
14. Environmental functional test.	5/6	*EDU tests actuator and controller functionality over entire temperature range in 1atm N2. Vibration and shock tests also.*		
15. Compliance of tested hardware to the requirements and drawings.	4/5/6	*Requirements met—see Test Report (DOC #TBD) for details.*		
16. Failure history and failure trend.	5/6	*Electronics packaging thermal cycle failures recorded in DOC #TBD.*		
17. Extent of changes required for project use.	5/6	*Add circuit changes for final worst case, modify PWB layout for quad op-amp, incorporate final Verilog additions into ASIC, and certify electronic parts per flight parts program plan.*		
18. QA paperwork for the delivered hardware (optional).	6	*QA data package for Actuator from Aeroflex, process documents for Electronics Assembly, Assembly and Inspection Data Sheet (AIDS) for environmental tests.*		
19. Delivery of end-item data package to MTP.	4/5/6	*Final Report describing environmental, functional and life test results (ICDs included). Design Drawings in JPL PDMS.*		

TRL assessment: **6**	*Cog-E/Task Manager Signature*	*Element Manager Signature*	*Technology Manager Signature*	*MTP/Project Manager Signature*

Figure 2. Example of TRL Evaluation for Hardware-related Technology Tasks

Software deliverables employed different evaluation criteria, and an example is shown in Figure 3. The top and bottom portion of the TRL evaluation form for software deliverables are the same as the hardware form with the exception of established TRL 4-6 definitions elaborated for software products. The example shown here describes Improved Visual Odometry technology developed under the MTP's MSL Focused Technology program.

Evaluation criteria required for TRL 4 assessment involve information pertaining to system requirements, description of operational environment, programming language, test conditions, compliance of tested software to requirements, and delivery of end-item data package.

Additional information requested for TRL 5-6 assessment are system interface, defects or idiosyncrasies resolved, software development process/documentation, and extent of change required for operational use. In order to achieve TRL 6, software benchmark using actual processing hardware (i.e., flight computer or equivalent) should be done, and hence software/algorithm performance including CPU/memory usage information is added.

Because the Improved Visual Odometry Software is a stand-alone "function call" and its external interactions focus on real-time processing of representative terrain imagery (and not dependencies on other software modules), we assessed that if the technology development effort achieves the results as described at the time of delivery (matured software development process and validation on a representative Mars terrain and rover platform), the technology is consistent with being at TRL 6, i.e., prototype implementations on full-scale realistic problems—engineering feasibility fully demonstrated in an operational environment partially integrated with existing systems.

TRL 4: *Standalone prototype implementations—experiments with full-scale problems or data sets.*	**MTP Technology Readiness Level Evaluation for Software** **TRL 6:** *Prototype implementations on full-scale realistic problems—engineering feasibility fully demonstrated in an operational environment partially integrated with existing systems.*	**TRL 5:** *Prototype implementations conform to target environment/interfaces—experiments with realistic problems using simulated interfaces to existing systems.*

Technology Product Description	Cognizant Engineer/Task Mgr	Organization	MTP Element	Element Manager	Date
Improved MER Visual Odometry Software	*Andrew Johnson*	*Section 347*	*MSLFT Surface Ops*	*Ed Wong*	*7/27/05*

EVALUATION CRITERIA	**Rq'd**	**Anticipated Status/Results at Delivery**	**Final Status/Results**	**Comments**
1. Functional requirements of the end product.	4/5/6	*Runtime optimization of MER VO algorithm (4X improvement) while maintaining the original motion estimation performance.*		
2. Description of "operational environment" or flight-like development environment.	4/5/6	*Mars Terrain, MSL rover, and MSL Navcam/Hazcam camera configurations.*		
3. Flight/ground software architecture/system interfaces.	5/6	*Function call through flight software.*		
4. Programming language.	4/5/6	*C++*		
5. Software/algorithm performance (including CPU/memory usage).	6	*15sec/update with 3X MER processor speed, memory usage TBD*		
6. Test environment.	4/5/6	*JPL Mars Yard, FIDO hazcams and navcams, and CLARAty software architecture.*		
7. Unit testing.	4/5/6	*MER-A and MER-B navcam (256×256) data sets, Rocky8 hazcam (640×480) data collected from JPL Mars yard, MSL-like navcam data set on LAGR vehicle.*		
8. Test plan and test case specifications.	4/5/6	*see VO Validation Test Plan (Doc #TBD).*		
9. Defects or idiosyncrasies resolved.	5/6	*Major defects documented as part of Final Report.*		
10. Software development process (configuration management and risk mitigation included).	5/6	*CVS configuration control applied, and VO software validated prior to MSL use.*		
11. Software documentation.	5/6	*Functional Design Document (Doc. #TBD) and Validation Test Report (Doc #TBD).*		
12. Compliance of tested software to the requirements.	4/5/6	*Requirements met—results described in the Final Report.*		
13. Extent of changes required for operational use.	5/6	*Need to add a top-level runtime interface and diagnostic features.*		
14. Delivery of end-item data package to MTP.	4/5/6	*Final Report, VO software and associated documentation included unit test cases.*		

TRL assessment: 6	*Cog-E/Task Manager Signature*	*Element Manager Signature*	*Technology Manager Signature*	*MTP/Project Manager Signature*

Figure 3. Example of TRL Evaluation for Software-related Technology Tasks

In summary, with the above forms/process for evaluating TRL status of technology deliverables, we efficiently expand the TRL definition information and provide enough flexibility for gathering needed technology-infusion information as well as assessing the TRL state for a broad range of technology products.

IV. Conclusion

Mars Technology Program has been developing advanced technologies needed for future Mars missions. Base Technology Program Element of Mars Technology Program addresses technologies that are applicable for multiple missions and can be characterized as longer term, higher risk, and high payoff technologies. These technologies are acquired primarily via competed NASA NRA process. In this paper, we presented an overview of MTP Base Technology Program and its current technology portfolio. Additionally, a new process to evaluate technology maturity has been introduced. We anticipate to apply this process on all tasks funded by MTP to provide a more realistic and accurate assessment on the state of the technology development.

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